Available online at www.sciencedirect.com
ScienceDirect
Procedia Engineering 5 (2010) 697–700
Procedia Engineering
www.elsevier.com/locate/procedia

Proc. Eurosensors XXIV, September 5-8, 2010, Linz, Austria

# SEM/FIB for characterization of nanosized imagers

A. Vilà[a]*, A. Comerma[b], J. Trenado[b], A. Arbat[a], D. Gascon[b], L. Garrido[b], A. Diéguez[a]

*a Electronics Department, Physics Faculty, University of Barcelona, C/Martí I Franqués 1, 08028-Barcelona, Spain*
*b Structure and Matter Constituents, Physics Faculty, University of Barcelona, C/Martí I Franqués 1, 08028-Barcelona, Spain*

**Abstract**

Electron beams of Scanning Electron Microscope (SEM) and dual-beam Focused Ion Beam (FIB) have been used to characterize a Geiger-mode Avalanche Photodiode (GAPD) array. The main advantage of those electron beams is the spot-size unprecedent resolution compared to the laser beams typically used for the characterization of optical imagers. Operation mode is also different, as instead of generating electron-hole pairs due to photon absorption, electrons are generated by the high energy injected electrons.

The GAPDs used have been fabricated with a conventional CMOS process. They are excellent for the purpose of this experiment because of their very high intrinsic gain and speed, giving rise, when properly biased, to a large output signal as a consequence of detected photons or ionizing particles. The detected counts due to injected particles have been correlated with Montecarlo simulations (Penelope) of the injected charge in the interaction region.



*Keywords: APDs; characterization; SEM; imaging*

## 1. Introduction

Single-photon avalanche diodes fabricated by conventional planar technology on silicon can be used as particle and photon detectors with high intrinsic gain and speed. Excellent single-photon sensitivity can be achieved when operating in Geiger mode (Geiger Avalanche Photodiode, GAPD), obtained when biasing the diode above the junction breakdown voltage. In this metastable stage, the first generated e-h pair is capable of triggering the avalanche multiplication of carriers, which is self-maintained until saturating a high output current. A fast rise-time current pulse is then generated, its leading edge marking the event of the photon absorption or particle interaction with the sensor with picosecond accuracy. An external circuit connected to the diode, as a series resistor quenching the avalanche, terminates the current increase. Typical value of the gain achieved exceeds $10^9$. According to all that, arrays of Geiger-APD cells can be used in fast particle detection [1], single-photon counting and time-correlated single-photon counting [2], provided minimum crosstalk and dead area between individual cells.

* Corresponding author. Tel.: +34-034039170; fax: +34-934021148.
*E-mail address*: anna.vila@ub.edu.


doi:10.1016/j.proeng.2010.09.205

The most common setup to characterize optical imagers and particle detectors consist in using a laser beam for analyzing most important aspects such as the sensitivity of individual pixels or crosstalk. The better spot size achievable is not below 1µm, which limits the possibilities of studying modern imagers based on pixels with sizes in the nm range [3]. In this work, a new method for fully characterizing an APD array made in CMOS technology is demonstrated using nm-sized spots. The controlled electron beam from a Scanning Electron Microscope (SEM) or a dual-beam Focused Ion Beam (FIB) machine have been used to experimentally demonstrate the capabilities of the studied APDs.

## 2. Experimental

An array of 8 APDs (20x100µm$^2$) has been fabricated in Austria MicroSystems, AMS, 0.35 µm technology. As shown in fig. 1, they consist on shallow P$^+$N junctions terminated in PN deeper guard rings to avoid electric field concentration and premature breakdown at edges. In our experiment, all 8 APDs were built in a shared N-well (common cathode) with different spacing between them (fig. 2). Each APD is connected to its own quenching resistance (270 kΩ), and a buffer decouples every APD output from the load (fig. 3). This setup enables to monitor the diode reverse current with a fast digitizing oscilloscope with controlled persistence.

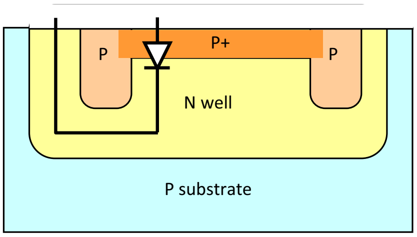


*Fig. 1: Cross section of the analyzed APDs, showing the P+N active junction and the guard ring.*

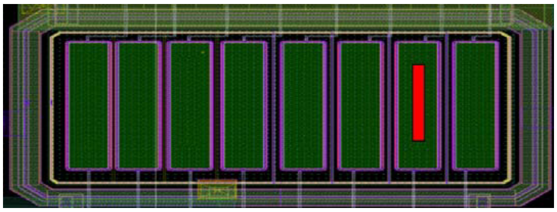

*Fig. 2: Layout of the GAPD array, showing 8 devices 20x100 µm$^2$.Active P+ zones appear in green, Pguard ring in pink, and the test area in red.*

A controlled ion/electron beam produced in a SEM or FIB machine is accelerated, collimated into a diameter of around 1 nm and scanned though different APDs in a controlled way. For the present experiment, the electron beam of a FEI Strata 235 Dual-Beam FIB machine is used. The quenching and amplifying circuitry was mounted in a PCB inside the vacuum chamber while display and control tools were kept outside. Fig. 4 presents the complete experimental setup. Electron beam energy in our SEM/FIB is accelerated to energy in the range from 400 eV to 30 keV, in a spot diameter ranging from 0.4 to 37.4 nm, with intensities between 0.0025 and 36.9 nA.

## 3. Results and discussion

Moving the beam across different APDs in the array allows determining the dead area and evaluating the noise characteristics of the detector, in particular cross-talk. Fig. 5 presents a preliminary measurement for 4 different APDs in the array (numbers 1, 3, 5 and 7). The electron beam is incident on the pink channel and the other 3 do not show any evidence of cross-talk. Only electronic noise is transferred between signals, due to non-optimized transmission, and some dark count is visible in the cyan channel. The routine used to count events in this kind of experimental patterns is based on selective-waveform peak detection and is able to ignore noise.

The observations have been correlated with Monte Carlo calculations with Penelope [4]. Fig. 6 summarizes the results for the calculated transmission of a 30keV electron beam across a typical passivating layer composed by $SiO_2$ and $Si_3N_4$ for a range of thicknesses. The measurements made in SEM/FIB showed that the activation energy for our APDs is around 22.5 keV, what after comparison with the previous graph allows the determination of the actual passivation thickness in the devices. This date has then been taken as a known parameter for the next calculations of the electron-beam ratio which is transmitted, absorbed and backscattered by the different passivation layers, summarized in figure 7. As a result, the actual ratio of the electron beam which is able to cross the passivation stack and arrive to the APD active zone can be deduced to be around 14%. For the experiment, an electron beam accelerated to 30 keV and collimated to 1 nm diameter with an intensity of 0.154 nA was directed to

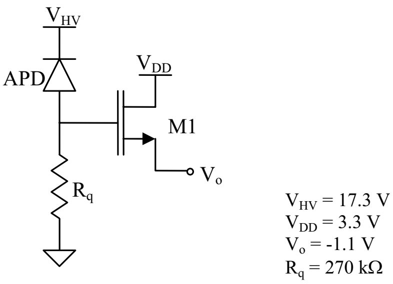


*Fig. 3: Schematics of the detection circuit, showing quenching resistance and amplifying buffer.*

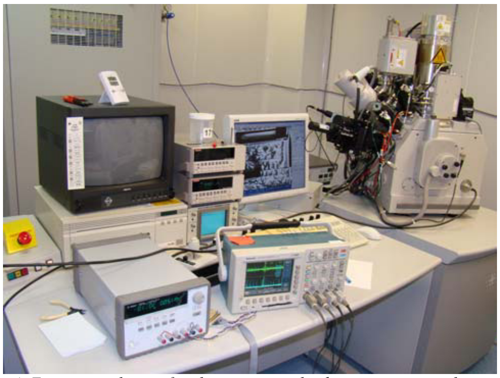

*Fig.4: Experimental setup for characterizing the detection circuits, showing the FIB/SEM machine, oscilloscope and power sources.*

the surface of the APDs array, what implies around $10^9$ incident electrons/s in a 3.14 $nm^2$ area, or 300 electrons/s·$\mu m^2$. Penelope simulator suggests that among them, around 140 electrons are transmitted across the passivation layers per microsecond.

However, the SEM/FIB tool does not give a fixed intensity for every electron-beam acceleration, and consequently, the calculation must be normalized to the actual given intensity. Moreover, the dead time and the Geiger operation mode itself must also be taken into account to compare with experiments. Every APD presents a detection dead time due to the time it needs to release the generated charge and return to its previous working point. This time depends on the capacities and resistances in its related circuitry, and for our detectors it is measured to be 200 ns. So, the maximum number of events detected during the measuring time (1 ms) is 5000. On the other hand, the Geiger operation mode gives maximum gain for minimum charge generated in an event, what implies maximum output independently of the amount of particles which are generating the event. So, it is necessary to consider the average number of particles, $\mu$, which arrive to the detector during every 200 ns window. As the beam can be described by the Poisson statistics, the probability of having a window without any event is given by $p(0) = \exp\mu$, and the expected number of windows with at least one event (what means the number of detected events) is then $\#counts = 5000\cdot(1-\exp\mu)$.

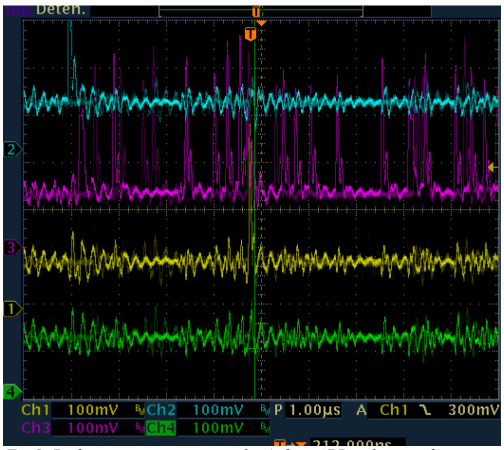


*Fig.5: Preliminary measurements for 4 close APDs, showing detection in the pink channel and reduced cross-talk for the other ones.*

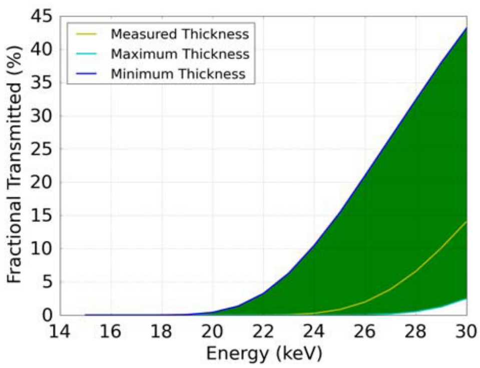


*Figure 6. Transmitted electrons after Penelope calculations, across passivation layer as a function of the beam energy*

This correction has been applied to our Monte Carlo simulations after calculating $\mu$, and the results are presented in fig. 8. A saturation effect in electrons detected for large incident intensities should only be visible when detection approaches its limit. And this effect is visible in our experimental results, suggesting that the studied APDs are counting with high efficiency, close to its own limit. The absolute value to which detection saturates is lower than the expected value (5000 electrons/pixel), what means that not-optimized electronics is limiting the actual detection.

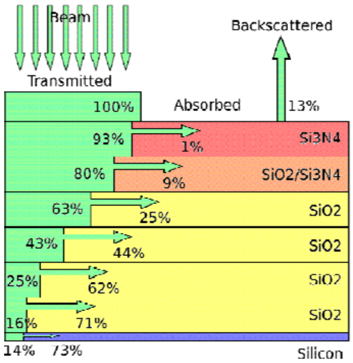


*Fig. 7: Transmitted electrons beams after direct Monte Carlo simulation for different passivation layers..*

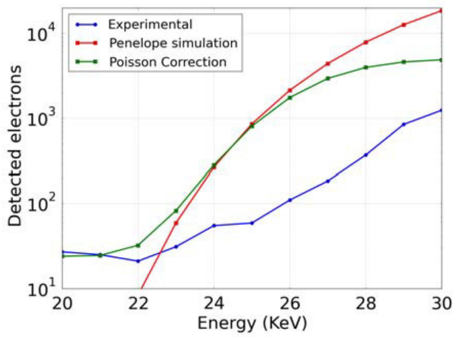


*Fig. 8: Correlation between Monte Carlo simulations and experiment (in blued). Direct simulations (in red) have been corrected for Poisson distribution and APD dead time (in green).*

## Conclusions

This work assesses the use of the beams from SEM and FIB to characterize particle detection in solid-state devices such as GAPDs. The demonstrated abilities provide a cost-effective fast and precise method for characterizing modern CMOS image sensors. Current limitations are mainly due to electronic noise transferred between signals by a non-optimized electronics. The saturation effect observed in electron detection, in agreement with Monte Carlo simulations corrected by Poisson's distribution, indicates that our APDs are counting electrons with high efficiency. Consequently, this work proves that GAPDs can also be used to construct an electron sensitive imager for scanning and transmission electron microscopy (SEM and TEM) instruments.

## Acknowledgements

This work has been partially supported by the Spanish project "Desarrollo de nuevas tecnologias en aceleradores y detectores para los futuros colisionadores de fisica de particulas", coded FPA 2008-05979-C04-02.

## References

[1] C Stapels, M Squillante, W Lawrence, F Augustin, J Christian. CMOS-based avalanche photodiode for direct particle detection. *Nucl. Inst. and Meth. A* 2007; **579**:94-8.

[2] M Ghioni, A Gulinatti, I Rech, F Zappa, S Cova. Progress in silicon single-photon avalanche diodes. *IEEE Journal of selected topics in* quantum electronics 2007; 13:852-862.

[3] J-H Park, S-H Seo, I-S Wang, H-J Yoon, J-K Shin, P Choi, Y-Ch Jo, H Kim. Active Pixel Sensor Using a 1x16 Nano-Wire Photodetector Array for Complementary Metal Oxide Semiconductor Imagers. Jap J Appl Ph 2004; 43(4B):2050–2053.

[4] J Baro, J Sempau, J-M Fernandez-Varea, F Salvat. PENELOPE: An algorithm for Monte Carlo simulation of the penetration and energy loss of electrons and positrons in matter. Nucl. Instr. Meth. Phys. Res. B 1995;100, 31-46.